A Study of $3\pi$ production in $\gamma p \rightarrow n\pi^+\pi^+\pi^-$ and $\gamma p \rightarrow \Delta^{++}\pi^+\pi^-\pi^-$ with CLAS at Jefferson Lab

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Photoproduction of $3\pi$

- Exotic $\pi_1(1600) \rightarrow 3\pi$
  - Has a rich and controversial history

- Theoretical work suggests enhanced hybrid production with photon beams
  - Expect exotic meson production equal to $q \bar{q}$ meson production

- Very little photoproduction data events
  - Resents results from CLAS
  - Upcoming results from GlueX/CLAS12

- $n3\pi$ and $\Delta^{++}3\pi$ are complimentary channels
Jefferson Lab

CLAS spectrometer
Using the CLAS-g12 dataset we selected events with three charge pions, measured by the CLAS spectrometer and identified a neutron by energy and momentum conservation.
Enhance Peripheral Production

\[ \gamma p \rightarrow n \pi^+ \pi^+ \pi^- \]

\[ \begin{align*}
\text{Mass}(n, \pi^+) & \quad (\text{GeV}/c^2) \\
\text{Mass}(n, \pi^-) & \quad (\text{GeV}/c^2) \\
\text{Mass}(\pi^+ \pi^+ \pi^-) & \quad (\text{GeV}/c^2)
\end{align*} \]
Further Reducing the Baryon Background

$$\gamma p \rightarrow n \pi^+ \pi^+ \pi^-$$

$$\theta_{lab}[\pi_{\text{slow}}^+] < 25^\circ$$
Features of the $3\pi$ sample

$\gamma p \rightarrow n \pi^+ \pi^+ \pi^-$

- **Mass** $(\pi^+ \pi^+ \pi^-)$
  - $M_{3\pi} < 1.5 \text{ GeV}$
  - $M_{3\pi} > 1.5 \text{ GeV}$

- **Mass** $(\pi^- \pi_{\text{slow}})$
- **Mass** $(\pi^- \pi_{\text{fast}})$
- **Mass** $(\pi^- \pi_{\text{fast}})$

- **Entries**
  - 528898
  - 328323
  - 184774
A mass independent pwa is performed using an event based likelihood fit.

To calculate the amplitudes we used helicity formalism in the reflectivity basis using the isobar model:

$$I(\tau) = \sum_{\kappa,\epsilon} |\sum_{\alpha} \epsilon^{\kappa} V_{\alpha}^{\epsilon} A_{\alpha}(\tau)|^2$$

For the current fit, a total of 17 partial waves were used in the high mass region and 13 partial waves in the low mass region.
Features of the partial waves of the $3\pi$ System for the $\gamma p \rightarrow n \pi^+ \pi^+ \pi^-$

- **Mass** $(\pi^+ \pi^+ \pi^-)$
  - $M = 1.318$ GeV
  - $\Gamma = 0.105$ GeV

- **Mass** $(\pi^+ \pi^+ \pi^-)$
  - $M = 1.200$ GeV
  - $\Gamma = 0.367$ GeV

- **Intensity of 2++ D waves**

- **Intensity of 1++ S waves**

- **Phase difference between 1++1-S and 2++1-D waves**

- **Phase difference between 1++1+S and 2++1+D waves**

*Curve is just to guide the eye*
Features of the partial waves of the $3\pi$ System for the $\gamma p \rightarrow n\pi^+\pi^+\pi^-$

- **Intensity of 2-+ S waves**
  - $M = 1.670$ GeV
  - $\Gamma = 0.260$ GeV

- **Phase difference between 1-+1-P and 2-+1-S waves**

- **Intensity of 1-+ P waves**

- **Phase difference between 1-+1+P and 2-+1+S waves**

**Curve is just to guide the eye**

**Preliminary**
Using the CLAS-g12 dataset we selected events with four charge pions, measured by the CLAS spectrometer and identified a proton by energy and momentum conservation.
Kinematic Separation of the $\Delta^{++}$

$\gamma p \rightarrow \Delta^{++} \pi^{+} \pi^{-} \pi^{-}$

Momentum Difference:

$|\vec{p}_{\pi_1}| - |\vec{p}_{\pi_2}|$ (GeV/c)

Background $\Delta^{++}$

Signal $\Delta^{++}$

Background $\Delta^{++}$

Signal $\Delta^{++}$

$\text{Mass}(p, \pi_{\text{fast}}^+)$ (GeV/c$^2$)

$\text{Mass}(p, \pi_{\text{slow}}^+)$ (GeV/c$^2$)
Data Selection and Background Reduction

\[ \gamma p \rightarrow \Delta^{++} \pi^+ \pi^- \pi^- \]

+ \[ M_{p\pi_{\text{slow}}^{+}} < 1.35 \]

Events/40 (MeV/c^2)^2

\[ t' (\text{GeV/c}^2)^2 \]

Mass(\(p\pi\pi^-\pi_{\text{fast}}^-)) (\text{GeV/c}^2)

Mass(\(p\pi_{\text{slow}}\pi_{\text{slow}}^-)) (\text{GeV/c}^2)

Mass(\(p\pi_{\text{fast}}^-\)) (\text{GeV/c}^2)

Mass(\(\pi_{\text{slow}}^+\pi_{\text{slow}}^-\)) (\text{GeV/c}^2)

Black \rightarrow \text{Data}

Red \rightarrow \text{Data with Cuts}

Blue \rightarrow \text{MC with Cuts}
Features of the $3\pi$ sample

\[ \gamma p \rightarrow \Delta^{++} \pi^+ \pi^- \pi^- \]

\[ \text{Mass}(\pi^+ \pi^- \pi^-) \quad \text{GeV}/c^2 \]

\[ M_{3\pi} < 1.5 \text{GeV} \]

\[ (\text{GeV}/c^2)^2 \]

\[ M^2(\pi^+, \pi^-_{\text{fast}}) \quad (\text{GeV}/c^2)^2 \]

\[ M^2(\pi^+, \pi^-_{\text{slow}}) \quad (\text{GeV}/c^2)^2 \]

\[ M^2(\pi^+, \pi^-_{\text{fast}}) \quad (\text{GeV}/c^2)^2 \]

\[ M^2(\pi^+, \pi^-_{\text{slow}}) \quad (\text{GeV}/c^2)^2 \]

\[ M_{3\pi} > 1.5 \text{GeV} \]
Partial Wave Analysis

- A mass independent pwa is performed using an event based likelihood fit
- To calculate the amplitudes we used helicity formalism in the reflectivity basis using the isobar model

\[ I(\tau) = \sum_{\kappa,\epsilon} \left| \sum_{\alpha} \epsilon^\kappa V_{\alpha, \epsilon} A_{\alpha}(\tau) \right|^2 \]

- For the current fit a total of 13 partial waves were used in the high mass region and 9 partial waves in the low mass region
Features of the partial waves of the $3\pi$ System for the $\gamma p \rightarrow \Delta^{++}\pi^+\pi^-\pi^-$

- **Intensity of $2^{++}$ D waves**
  - $M = 1.318$ GeV
  - $\Gamma = 0.105$ GeV

- **Intensity of $1^{++}$ S waves**
  - $M = 1.260$ GeV
  - $\Gamma = 0.367$ GeV

- **Phase difference between $1^{++}1-$S and $2^{++}1-$D waves**

- **Intensity of $1^{++}$ D waves**

Curve is just to guide the eye

Preliminary
Features of the partial waves of the $3\pi$ System for the $\gamma p \rightarrow \Delta^{++} \pi^+ \pi^- \pi^-$

**Preliminary**

leakage of $a_2(1320)$ into the P-wave

Total Intensity of 2-+ waves

The importance of the $J^{PC}=1^{-+}$ partial wave is still being investigated.
Summary

- $\gamma p \rightarrow n \pi^+ \pi^+ \pi^-$:
  - The $a_2(1320)$ and the $a_1(1260)$ are observed
  - The $\pi_2(1670)$ is observed
  - The $J^{PC}=1^{-+}$ appears to have no phase motion relative to the $\pi_2(1670)$

- $\gamma p \rightarrow \Delta^{++} \pi^+ \pi^- \pi^-$:
  - A first time PWA of the $\Delta^{++} 3\pi$ system
  - The $a_2(1320)$ and the $a_1(1260)$ are observed
  - The $\pi_2(1670)$ is observed
Back up slides


List of Waves used for the current Fit $\gamma p \rightarrow n \pi^+ \pi^+ \pi^-$

<table>
<thead>
<tr>
<th>$J^{PC}$</th>
<th>$M^e$</th>
<th>$L$</th>
<th>$Y$</th>
<th>Number of waves</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1^{++}$</td>
<td>$1^{-/+}$</td>
<td>$S,P,D$</td>
<td>$\rho(770),\sigma$</td>
<td>6</td>
</tr>
<tr>
<td>$1^{-+}$</td>
<td>$1^{-/+}$</td>
<td>$P$</td>
<td>$\rho(770)$</td>
<td>2</td>
</tr>
<tr>
<td>$2^{++}$</td>
<td>$1^{-/+}$</td>
<td>$D$</td>
<td>$\rho(770)$</td>
<td>2</td>
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Isotropic background wave

$M_{3\pi} < 1.4 \text{ GeV}$

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<td>$S,P,D$</td>
<td>$\rho(770),f_2(1270)$</td>
<td>6</td>
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Isotropic background wave

$M_{3\pi} > 1.38 \text{ GeV}$
List of Waves used for the current Fit $\gamma p \rightarrow \Delta^{++} \pi^+ \pi^- \pi^-$

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<th>$L$</th>
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</tr>
</thead>
<tbody>
<tr>
<td>1$^{++}$</td>
<td>1$^{-/-}$</td>
<td>$S,D$</td>
<td>$\rho(770)$</td>
<td>4</td>
</tr>
<tr>
<td>2$^{++}$</td>
<td>1$^{-/-}$</td>
<td>$D$</td>
<td>$\rho(770)$</td>
<td>2</td>
</tr>
<tr>
<td>2$^{-+}$</td>
<td>1$^{-/-}$</td>
<td>$P$</td>
<td>$\rho(770)$</td>
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Isotropic Background Wave

$M_{3\pi} < 1.4 \text{ GeV}$

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Isotropic Background Wave

$M_{3\pi} > 1.35 \text{ GeV}$
Intensity of 2+ S waves

\[ M = 1.640 \text{ GeV} \]
\[ \Gamma = 0.260 \text{ GeV} \]

Intensity of 1+ P waves

Phase difference between 1+1+P and 2+1+S waves

\[ \delta \phi \]

Curve is the phase motion of a pure 2+ wave only

Curves are the phase motion of a pure 2+ wave only

Preliminary